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Study on Design Compliance of Civil Turbofan Engine with the Requirements Defined in FAR 33.65

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Abstract

Engine surge and stall characteristics is an important safety issue that must be certificated before the engine type certificate (TC) approval. In this paper, design requirements of airworthiness regulation FAR 33.65 “Surge and stall characteristics” are established for five critical engine operation conditions, namely throttle transients, Bodie transients, starter assisted starts, windmill starts, and quick windmill relights. The design requirements consider all influencing elements analysis such as throttle level angle (TLA) movement, ambient temperature, inlet distortion, customer bleeding, power extraction, manufacturing/rigging/controlling tolerances as well as the critical engine condition analysis and pass/fail criteria for measuring design. Furthermore, one of the design requirements, inlet distortion, is selected to illustrate the simulation technique. This analysis technique uses the intake model as simulation object and aircraft crosswind as input conditions. Finally, the distortion intensity at the intake aerodynamic interface plane (AIP) is calculated by using CFD, which is one of the design inputs for engine stability analyses.

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Keywords: FAR 33.65; Design Requirements; Inlet Total Pressure Distortion

1. Introduction

The surge and stall phenomena may cause engine lose power at anywhere of the flight envelope. Non-recoverable surge and stall has caused a number of accidents with human casualties. Due to the criticality

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of engine surge and stall problems, the authorities are paying more and more attention to this issue. As a result, FAA adopted a more strict and definite regulation FAR 33.65 in 1974 [1]. Meanwhile, CAAC basically adopts FAR 33.65 requirement. Therefore, engine surge and stall characteristics must be certificated before the CAAC TC approval.

Based on the situations above, FAR 33.65 is selected to conduct a study which includes: 1) airworthiness analyses of FAR 33.65; 2) engine design requirements to comply with FAR 33.65; 3) crosswind simulation analysis for total pressure distortion intensity at the intake AIP.

2. Airworthiness analyses

FAR 33.65 was firstly issued in 1965. However, a commentator recommended revision of proposed FAR 33.65 to include reference to the allowable engine operating limitations in order to clarify that there could not be a finding of noncompliance in case of any undesired effects resulted from operations beyond those limitations. The section is intended to apply only to operations that are within allowable operating limitations as set forth in the manufacturer's operating instructions and the requirement is revised to make this clear. FAA finally accepted the recommendation of the commentator, and revised the regulation in 1974.

Study to the latest regulation reveals that, the design of engine needs to consider throttle transients, Bodie transients, starter assistance starts, windmill starts, and quick windmill relights in terms of surge and stall in order to satisfy the requirements of compressor aero-dynamic stability, combustion stability, and structural strength.

3. Design requirements

3.1. Throttle transients stability

In the period of throttle transients operation, advance TLA within 1 second from Minimum Idle (M/I) to Maximum Takeoff (T/O), stabilize at T/O for several minutes. Then pull back TLA within 1 second from T/O to M/I, stabilize at M/I for several minutes (Fig. 1). Pass/fail criteria is that, during the operation, the engine does not surge and stall, or the surge and stall does not cause flameout, structural failure, overtemperature, or failure of the engine to recover thrust.

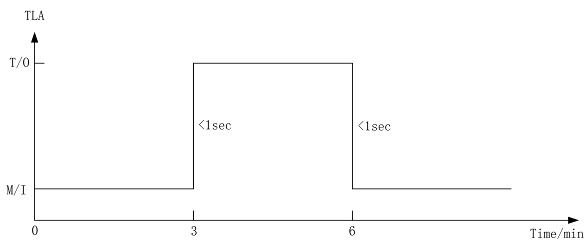

Fig. 1. TLA changes during throttle transients

3.1.1. Critical points

According to the regulation requirements, engine throttle transients operations should meet the pass/fail criteria described in paragraph 3.1.1 at any point in the operating envelope. Therefore, the most critical points need to be selected, where, if the engine throttle transients are successfully verified, the engine throttle transients would certainly meet the pass/fail criteria at other points.

It is a misconception to consider engine typical operating points within the envelope as critical points (such as sea level maximum takeoff, high pressure altitude maximum takeoff, maximum climb up, and maximum cruise, etc.) in terms of engine throttle transients. In fact the most critical points which need to be used for surge and stall characteristics assessment are located in the inflexions of the operating envelope boundary, showing as a-g in Fig. 2. In Fig. 2, H_{max} is the maximum altitude limit of the engine, Ma_{max} is the maximum Mach number limit of the engine.

Engine normal operation generally does not operate at these most critical points. However, engine has to be able to operate stall-free at anywhere of the flight envelope. Therefore, the most effective way is selecting the inflexions on the envelope boundary as most critical points to verify the engine capability in the entire flight envelope.

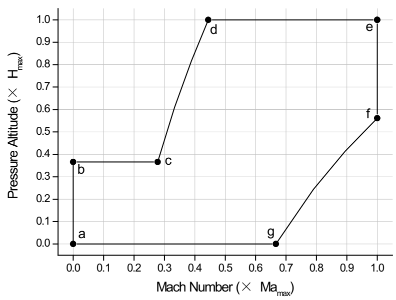

Fig. 2. Critical points of engine throttle transients

3.1.2. Ambient temperature

According to the regulation requirements, engine throttle transients should meet the pass/fail criteria described in paragraph 3.1.1 at limiting inlet air temperature.

Limiting ambient temperature includes high temperature and low temperature. High temperature may cause the decreasing of the fan, booster, or compressor stall margin, and the increasing of the fuel volatility, which may lead to the engine surge or stall, fuel autoignition, fuel nozzle coke deposition, and the engine overtemperature. Low temperature may cause the increasing of fuel and oil viscidity, which leads to poor fuel atomization, decreased combustion efficiency and increased accessory gear torque.

Each type of engine has its own defined temperature envelope, in which limiting air temperature can be selected for a critical design point of engine throttle transients corresponding to a pressure altitude. A schematic of engine temperature envelope is shown as Fig. 3. For an example, for critical point f where the pressure altitude is about $0.55 \times H_{max}$, the limiting high temperature and low temperature are approximately $-1.3 \times T_{max}$ and $0.1 \times T_{max}$ respectively. T_{max} is the maximum temperature limit of the engine.

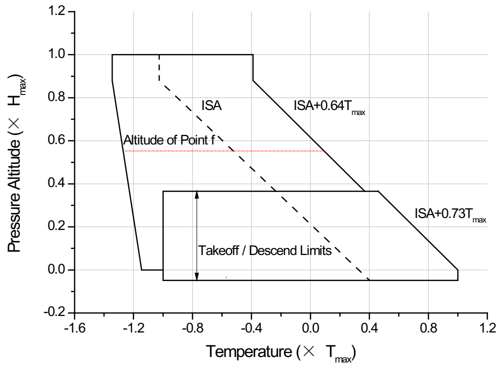

Fig. 3. Engine temperature envelope

3.1.3. Inlet distortion

According to the regulation requirements, engine throttle transients should meet the pass/fail criteria described in paragraph 3.1.1 under limiting inlet distortion.

Inlet distortion may be caused by crosswind and angle of attack during aircraft operation. Therefore, the intensity of crosswind and the range of angle of attack should be defined by aircraft manufacturer.

3.1.4. Customer bleed and power extraction

According to the FAR 33.89(a)(3), engine throttle transients should meet the pass/fail criteria described in paragraph 3.1.1 under the following engine loading conditions [2]:

- No bleed air and power extraction for aircraft use.
- Maximum allowable bleed air and power extraction for aircraft use.
- An intermediate value for bleed air and power extraction representative of that which might be used as a maximum for aircraft during the period from approaching to landing.

3.1.5. Manufacturing/rigging/controlling tolerances

Engine throttle transients should meet the pass/fail criteria described in paragraph 3.1.1 under the worst combinations of the manufacturing/rigging/controlling tolerances of the following controlling mechanisms:

- Fuel regulation.
- Variable bleed valve.
- Variable stator vane.
- High pressure compressor (HPC) bleeding.

3.2. Bodie transients

In the period of Bodie transients operation, pull back TLA within 1 second from T/O to M/I, when HPC reaches the minimum surge margin, advance TLA immediately within 1 second from M/I to T/O, stabilize at T/O for several minutes (Fig. 4). During the operation, the engine does not surge and stall, or the surge and stall does not cause flameout, structural failure, overtemperature, or failure of the engine to recover thrust.

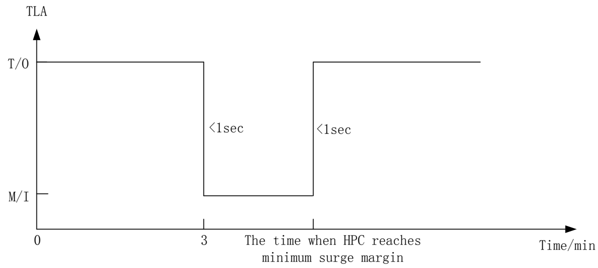

Fig. 4. TLA changes during Bodie transients

However, it is usually not practical to confirm the time and N2 speed when HPC reaches minimum surge margin by one time TLA pulling back/advancing cycle. Actually, the normal practice is: consider steady-state M/I core speed $N2_{idle}$ as cardinal speed, $\Delta N2$ as speed increment, n as time increment, when N2 decreased to $N2_{idle} + n \times \Delta N2$ after pulling back TLA from T/O to M/I, advance PLA immediately from M/I to T/O, as shown in Fig. 5. This method can catch minimum surge margin of HPC precisely without predicting the time when HPC reaches minimum surge margin in advance.

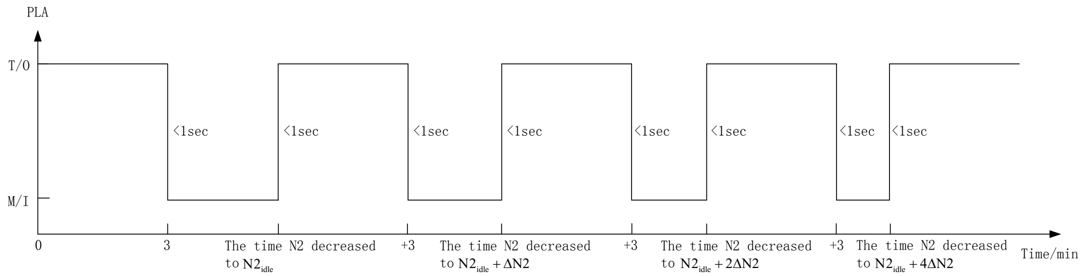

Fig. 5. Practical TLA changes during Bodie transients

The design requirements of engine Bodie transients are the same as throttle transients described in section 3.1.2 to 3.1.6.

3.3. Starter assistance starts and windmill starts

In the period of assistance starts and windmill starts operation, the engine does not surge and stall, or the surge and stall does not cause flameout, structural failure, or overtemperature.

3.3.1. Critical points

It is similar to throttle transients that the critical points of starter assistance starts (SAAS) are located in the inflexions in assistance start envelope boundary, and the critical points of windmill starts (WM) are located in the inflexions in windmill start envelope boundary, shown as points h to u in Fig. 6. It is worthwhile to note that not all the turning points in the assistance start envelope boundary are selected as critical points of SAAS. The turning points not being selected are those located in the common boundary of assistance start envelope and windmill start envelope, which will be considered as critical points of severe more WM. Therefore, the critical points of SAAS are points h to m, and the critical points of WM are points n to u, where both points n and o are quick windmill relight (QWRL) points at which the engine is able to windmill start shortly (usually less than 30 seconds) after flameout.

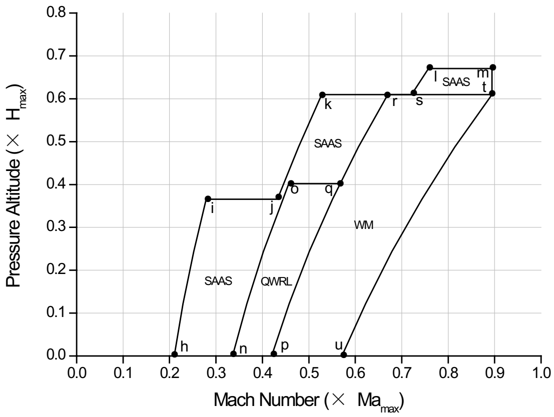

Fig. 6. Critical points of engine starter assistance starts

The other design requirements of engine SAAS and WM are the same as throttle transients described in section 3.1.3 to 3.1.6, except for the critical points selection above.

4. Crosswind simulation analyses

Inlet total pressure distortion is one of the design requirements to comply with FAR 33.65, as presented in paragraph 3.1.4. Inlet distortion may be caused by crosswind or angle of attack during aircraft operating. Generally the circumferential distortion descriptor $(\Delta PC/P)_{avg}$, which is defined in paragraph 4.2, is used as the input parameter during stability assessment because of its ease of use and simplicity. $(\Delta PC/P)_{avg}$ is described as the intensity of the total pressure distortion which is usually caused by crosswind or angle of attack from the freestream, and has a unique value corresponding to a certain crosswind intensity or angle of attack.

As suggested in the present paper, simulations and analyses should be performed to acquire the desired $(\Delta PC/P)_{avg}$ from airworthiness regulation text. Details of simulations and analyses work are described below.

4.1. Choice of CFD requirements

In this section, a typical intake designed for a high bypass ratio commercial turbofan engine with the subsonic inflow, is selected in this study, and numerical simulations are conducted as per the crosswind requirement from the aircraft.. Subsequently, the distortion index at the intake outlet is calculated. The geometry of the intake is schematically shown in Fig. 8, together with relevant dimensions, where station i and 2 respectively refers to the lip (high-light) and AIP (the cross section at the tip of the spinner) of the intake. The X-Z plane coincides with the intake symmetry plane with the X-coordinate pointing downstream. The intake highlight is defined at x = 0. The AIP is located at x/D_2 equal to 0.40, and D_2 is the diameter at AIP. The dip angle at the intake lip is 4 degrees.

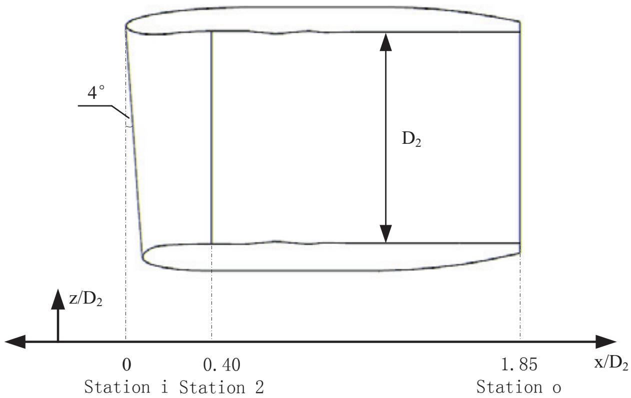

Fig. 8. Schematic of the intake geometry

In the simulation, the outflow condition is specified at the interface plane with the fan, and the interaction between the intake and the fan is neglected. Since the flow at AIP is subsonic, the static pressure is imposed at the intake outlet as a usual strategy. The static pressure can be calculated from mass flow rate customarily known, by assuming a locally 1D isentropic condition, yielding a direct relationship between mass flow rate and static pressure [4]. The back pressure ratio is set as $P_b/P_0 = 0.8389$, where P_b is the back pressure on the outlet and P_0 is the freestream static pressure.

Since there is no known information about how the static pressure is distributed, it is important to minimize the influence of any a priori specification of its value and profile. Hence, the computation domain is extended beyond AIP with additional straight section of length $L_2 = x_o - x_2$ [3], located in station o as shown in Fig. 8. It is verified after the solution is converged that in this extended section the flow becomes nearly unchanged towards the end and the static pressure becomes uniform, but the pressure at AIP still varies at both radial and circumferential directions. Fig. 9 shows the computation domain used in this study.

The simulation is based on solving three-dimensional Reynolds-averaged Navier-Stokes equation with closure by the two-equation $\mathrm{k} - \varepsilon -$ Realizable model. The crosswind strength is specified to be 35 knots, and the sideslip angle is 14.84 degrees, which yield a crosswind Mach number of 0.053 and freestream Mach number of 0.207 at the standard sea level dry air condition.

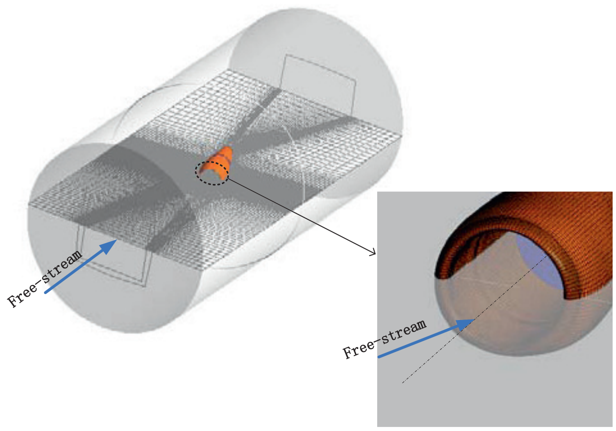

Fig. 9. Computation domain used in this study and an enlarged view of the intake entrance

4.2. Analyses of CFD results

As shown in Fig. 10, the pressure contours are displayed at three sections inside the intake. These sections are located at the AIP, the outlet, and in the middle of the AIP and the outlet. It can be seen that the static pressure is distributed uniformly at the outlet section which verifies the extend section L_2 described above is enough to form an acceptable computation domain.

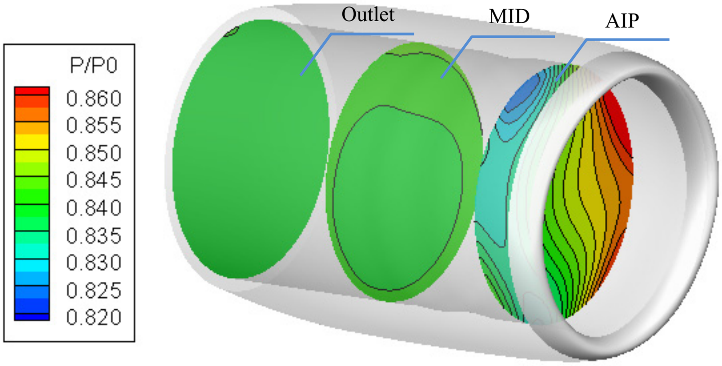

Fig. 10. Pressure contours at three sections inside the intake

Fig. 11 reveals the static pressure distributions on the X-Y plane. It can be seen that along the top section the pressure decreases raplidy forward and near the throat, and rises a little from the throat to the AIP. Near the AIP, the pressure near the bottom section is slightly higher than that near the top section due to the crosswind sideslip direction. Fig. 12 reveals the Mach number distributions and the streamlines on the X-Y plane.

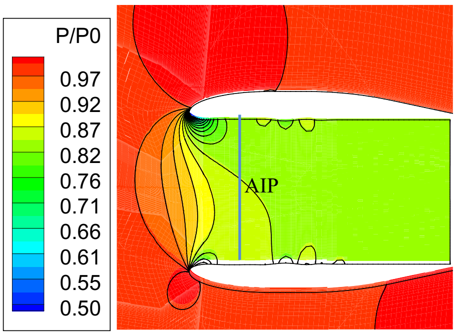

Fig. 11. Static pressure contours on the X-Y plane

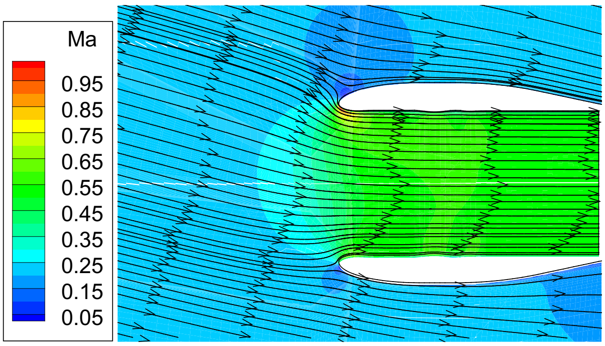

Fig. 12. Mach number contours and streamlines on the X-Y plane

Fig. 13 reveals the total pressure contours at AIP. and a asymmetric distribution is clearly shown. There is a low total pressure region skewed towards the windward side of the nacelle, which represents a significant circumferential distortion.

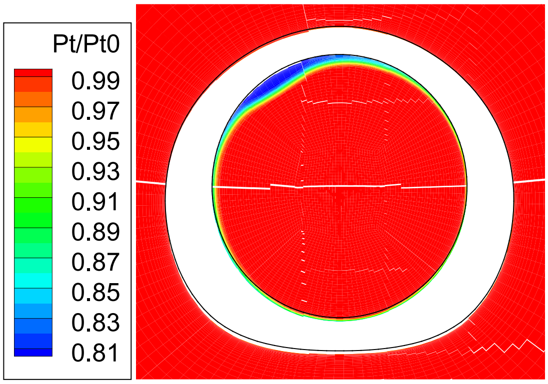

Fig. 13. Total pressure contours at AIP

The circumferential distortion descriptor $(\Delta PC/P)_{avg}$, defined according to the SAE standard [5], is used here to describe the circumferential distortion. $(\Delta \mathrm{PC/P})_{\mathrm{avg}}$ is calculated by averaging total pressure distortions over 5 equally area-weighted rings [3]:

$$\left(\frac{\Delta PC}{P}\right)_{avg} = \frac{1}{5}\sum_{i=1}^{5}\left(\frac{\overline{P_t} - \overline{P_{t,low}}}{\overline{P_t}}\right)_i \tag{1}$$

Where:

$$\overline{P_{t,i}} = \frac{1}{360}\int_0^{360} P_{t,i}(\theta)d\theta \;\; (Ring\ Average\ Total\ Pressure)$$

$$\overline{P_{t,low,i}} = \frac{1}{\theta_i^-}\int_{\theta_{1,i}}^{\theta_{2,i}} P_{t,i}(\theta)d\theta \;\; (Average\ Low\ Total\ Pressure)$$

$P_{t,i}(\theta)$ is the total pressure at circumferential angle θ, in the *i-th* ring.

θ_i^- is the circumferential extent of the low total pressure region, in which the total pressure is lower than the averaged total pressure of the ring.

$\theta_{1,i}$ and $\theta_{2,i}$ are the lower limit and upper limit of the low total pressure region respectively.

In table 1, we present the resulting performance of the intake at AIP in terms of circumferential distortion descriptor $(\Delta PC/P)_{avg}$ and total pressure recovery ratio $(P_t/P_{t0})_{avg}$ at takeoff with crosswind.

Table 1. Intake performance in crosswind condition

$(\Delta PC/P)_{avg}$	$(P_t/P_{t0})_{avg}$
0.0206	0.9897

5. Conclusions

The design requirements of the engine's five critical characteristics, namely throttle transients, Bodie transients, starter assisted starts, windmill starts, and quick windmill relights which should be demonstrated in airworthiness regulation FAR 33.65, are studied, and the intake total pressure distortion intensity caused by crosswind in specified conditions are calculated using CFD. The main conclusions have been drawn as follows:

- In order to show design compliance of the engine’s five critical characteristics, it is necessary to quantify the design requirements as follows: critical points at the envelope, TLA movement, ambient temperature, inlet distortion, customer bleeding, power extraction, manufacturing/rigging/controlling tolerances as well as the pass/fail criteria.
- CFD method is used for the intake crosswind simulation at the engine takeoff phase. As a result, the circumferential distortion intensity described as $(\Delta PC/P)_{avg}$ at the intake AIP is calculated with value of 0.0206, which would be a design input for engine inlet distortion stability analyses.

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